resources

Communication

Abiotic Raw-Materials in Life Cycle Impact Assessments: An Emerging Consensus across Disciplines

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Abstract: This paper captures some of the emerging consensus points that came out of the workshop "Mineral Resources in Life Cycle Impact Assessment: Mapping the path forward", held at the Natural History Museum London on 14 October 2015: that current practices rely in many instances on obsolete data, often confuse resource depletion with impacts on resource availability, which can therefore provide inconsistent decision support and lead to misguided claims about environmental performance. Participants agreed it would be helpful to clarify which models estimate depletion and which estimate availability, so that results can be correctly reported in the most appropriate framework. Most participants suggested that resource availability will be more meaningfully addressed within a comprehensive Life Cycle Sustainability Assessment framework rather than limited to an environmental Life Cycle Assessment or Footprint. Presentations from each of the authors are available for download [1].

Keywords: abiotic natural resources; Life Cycle Assessment; minerals; mining; ore grades; reserves; resource availability; resource scarcity; safeguard subject; raw-materials

1. Introduction

On Wednesday 14 October 2015, a global group of approximately 50 experts from academia, consulting, regulators, primary industry, down-stream sectors and standards bodies gathered at the Natural History Museum London to exchange recent findings on the way that life cycle assessment is currently applied to the use of raw-materials.

In welcoming workshop participants, the hosts explained that the road travelled in developing Natural Resources as a safeguard subject (or Area of Protection (AoP)) in Life Cycle Impact Assessment (LCIA) had been a long one, but that some more recent milestones along the way served as useful background for the day's discussion. Namely, the mining industry (Euromines and the International Council on Mining & Metals (ICMM)) had held a series of key workshops during the years 2011–2014 to bring experts from within and outside the mining industry together to discuss Life Cycle Assessment (LCA) in the context of Resource Efficiency policies. This led to greater mining industry participation in other forums such as the European Commission Joint Research Centre Workshop on "Security of supply and scarcity of raw-materials: a methodological framework for sustainability assessment" in 2012 [2] and the 55th Discussion Forum on LCA (DF-55) held in Zurich in 2014 [3].

It was announced that the industry had drafted a journal article drawing upon its experiences with LCA and the knowledge of its exploration, geology, and economic experts that is now freely available from the International Journal of Life Cycle Assessment [4].

The authors of that article suggested that development of a globally agreed upon method for assessment of abiotic raw-material inputs in Life Cycle Impact Assessment (LCIA) could be characterized by a certain amount of *confusion*, *resistance* and *frustration* and that, according to Knoster *et al.* [5], this quite possibly stemmed, respectively, from the lack of a common *vision* across disciplines of the potential threat or impact to measure; from a lack of aligned *incentives* amongst the different experts for developing such a method; and therefore a general lack of *knowledge* sharing and data availability between disciplines. The Workshop hosts invited the participants to begin a process of improving the sharing of knowledge and the seeking of common goals at the Workshop.

All presentations at the Workshop are available for download [1].

2. Results and Discussion

2.1. Status and Limitations: The Data

The first session of the workshop centered on the data typically drawn upon for estimating potential environmental impacts on abiotic natural resources in LCA. These data are typically generated by or for the mining industry and its (financial) stakeholders, but also for various government departments. The discussions were therefore designed to increase LCA-practitioners' familiarity with mining.

2.1.1. Economics of Resource Supply and Use

Tom Brady (Chief Economist, Newmont Mining, Greenwich Village, CO, USA) presented a visual summary of the typical process of identifying and reporting Mineral Reserves from the perspective of a mining executive. Central to his presentation was the use of the Committee for Mineral Reserves International Reporting Standards (CRIRSCO) definitions to classify different materials identified during exploration work. Mine planning (both in terms of the size and shape of the proposed mine, but also the schedule and sequence of mining) guides the identification of different classes of Mineral Resources and Mineral Reserves. Successive iterations of sampling, data interpretation and mine planning alter the estimates of each—even after a mine begins operation (Newmont typically only reports Proven Mineral Reserves once a mine has been operating as designed for 12 months). This involves consideration of several modifying factors that include processing, metallurgical, economic, marketing, legal, environmental, socio-economic and geopolitical factors. In particular, Mineral Reserve estimates fluctuate greatly as assumptions about future commodity prices change.

As of 31 December 2014, Newmont Mining Gold Reserves varied by up to 30% depending on whether a gold price of USD 1100/ounce was assumed, or USD 1500/ounce. In addition, when metal prices are high, exploration expenditure and discoveries tend to increase such that new Mineral Resources more than make up for the Mineral Reserves extracted. Whereas LCIA methods often assume that the stock of Mineral Resources and Mineral Reserves is fixed and depleting, in fact they increase or decrease with fluctuations in availability of infrastructure, exploration budgets, geological knowledge, market prices, projected production costs and technology development.

2.1.2. Resource Data: The Providers' Perspective

Jane Hammarstrom (Co-Chief, Global Mineral Resource Assessment Project, USGS, Reston, VA, USA) presented an explanation of the information services that the USGS provides, underlining how it compiles estimates of global Mineral Resources and Reserves and also explaining how it provides science-based assessments of likely Undiscovered Mineral Resources. While USGS definitions of Mineral Resources and Mineral Reserves largely match those of CRIRSCO, estimates from different sources may lack consistency owing to the different needs of, say, government and individual mining companies. Depending on the purpose and the timeframe considered, estimation methods and professional judgments may differ (e.g., commodity price and production cost forecasts). Reserve figures are estimates and they are snapshots in time that depend on several factors including demand, exploration budgets, recycling rates, technology, economics, social license to operate and environmental performance and therefore should only be interpreted together with the accompanying qualitative information provided by the Survey. Therefore, the notion that reserve figures tell us how many years remain until a natural resource is depleted must be rejected. Copper data also demonstrate the falsity of the notion that as ore is mined reserves necessarily decrease (copper reserves doubled from 1990 to 2013). It is questionable which of the different estimates of Resources and Reserves provided by the USGS could plausibly serve as a basis for measuring resource depletion. Neither the USGS Reserve Base nor the theoretical world resources is an immediately obvious or justified choice.

2.1.3. Resource Data: The Users' Perspective

Ruth Allington (Treasurer of Pan-European Reserves & Resources Reporting Committee, CRIRSCO, Brussels, Belgium) presented an overview of CRIRSCO, its aims, history, make-up and governance. The CRIRSCO-aligned definitions of Mineral Resources and Mineral Reserves have a history stretching back at least as far as the 1980s, with broad acceptance globally. The accurate and reliable reporting of mineral exploration results, Mineral Resources and Mineral Reserves is fundamental not only to mining stakeholders (for transparency of commodity markets), but also to wider society including the LCA community. CRIRSCO requirements follow some main principles related to *transparency*, *materiality*, *competence* and *impartiality*. In-particular, the role of the Competent (Qualified) Person, as required by CRIRSCO-aligned reporting codes and standards [6], is critical to upholding those principles. The Competent Person is named publicly as being personally responsible for proper estimation of Mineral Resources and Mineral Reserves and is subject to potential disciplinary action from the relevant CRIRSCO-affiliated professional organization. When the Competent Person identifies a Mineral Reserve, it must be demonstrated and this was done through a thorough analysis of the modifying factors described by others (see above) including relatively volatile socio-economic aspects such as commodity price. It is argued that CRIRSCO and its Competent Person concept are the keys to stakeholder confidence in any public reporting of LCA results based on estimates of Mineral Resources or Mineral Reserves and the LCA community should beware of embracing this economic data without acknowledging its limitations for their environmental work. To do so gives rise to misleading results and, given the CRIRSCO principles of *transparency*, *materiality*, *competence* and *impartiality*, would raise an ethical issue.

2.2. Status and Limitations: The Methods

The second session of the workshop centered on the methods typically used to estimate potential environmental impacts on abiotic natural resources in LCA. These methods have typically been developed by academics or LCA practitioners in the context of overall LCA frameworks or software. The discussions were therefore designed to increase mining professionals' familiarity with LCA.

2.2.1. Drivers for LCA of Resource Supply and Use

Andrea Russell-Vaccari (Principal Consultant, Align Consulting, Sheridan, WY, USA) introduced LCIA and safeguard subjects (Areas of Protection), their state of development and decision-makers' needs related to abiotic raw-materials. For impact category selection, the International Organization for Standardization (ISO) recommends characterization methods for the AoP be broadly agreed, environmentally relevant and describing a "distinct identifiable environmental mechanism" [7]. The resource depletion impact category is hampered by insufficient understanding of the Natural Resources AoP and hence the issue to address [8]. This is due to the variability of concepts like resource availability over space and time. Figure 1 is a visual representation of the questions that stakeholders ask about abiotic raw-materials: from environmental impacts to economic impacts; from short-term effects to long-term effects; and from micro-economics (product systems) to macro-economics (whole economies). Whereas Abiotic Depletion Potential (ADP) is easy to assess for LCIA methodology developers (top right of Figure 1), the results are not meaningful for those in the other three quadrants of Figure 1.

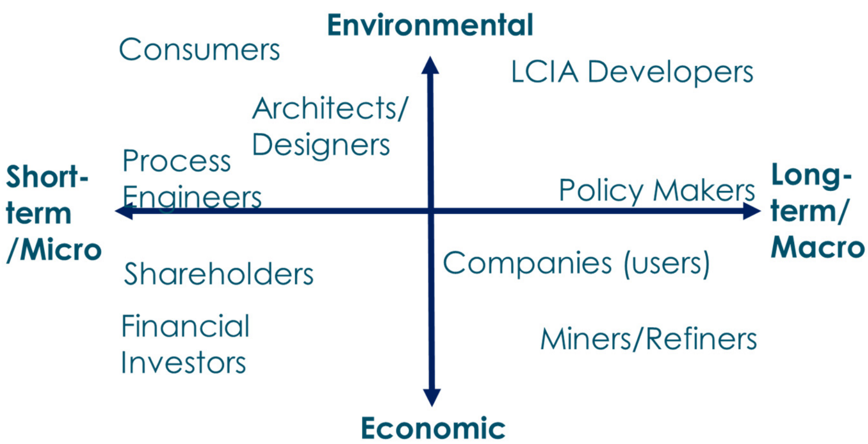

Figure 1. A proposed mapping of different decision-makers across a range of different abiotic raw material information needs (adapted from [9]).

The proposed constraint with which the assessment is made (Ultimate Reserve or Crustal Content) is so remote that it is of little relevance to decision-makers. *Availability* of materials is of more general concern. The sensitivity analysis of using other constraints, recommended by [10], demonstrates that the distinction between depletion and availability is critical, because it can actually be decisive for product selection. Because the needs of decision-makers are different to the environmental focus provided by LCIA and the AoP concept, abiotic raw-material assessment needs to expand beyond the confines of LCA and embrace other tools. LCIA alone is not able to provide adequately robust information for all decision making.

2.2.2. Abiotic Depletion Potential Method, Its Variants and Example Results

Jeroen Guinée (Assistant Profesor, CML, Leiden, The Netherlands) is one of the main authors of the original ADP method most commonly used in LCA and he presented a history of the philosophy behind it. There can be no scientifically correct method for assessing potential environmental impacts on abiotic natural resources because the concept of "resource" straddles the economic–environmental divide and none of the physical parameters or results can actually be validated empirically. This requires LCA practitioners to make a number of philosophical choices—rather than use inductive reasoning—when developing resource assessment models. Choices include a definition of the resource problem to be addressed; whether or not to consider it a problem distinct from deterioration of the environment; and which data to use. While availability, criticality, *etc.* are also of interest, the Institute of Environmental Sciences (CML) ADP method only addresses depletion of a resource in terms of reduction of the geological stocks present on Earth (Ultimate Reserve or Crustal Content). LCA results are highly sensitive to deviations from the use of Ultimate Reserves (Crustal Content). CML definitions differ from those of CRIRSCO because "resource" is commonly used to describe a category of mineral occurrences as well as to a material in its own right and is therefore ambiguous (One should perhaps rather refer to Natural Resources as natural materials or raw-materials, in order to better distinguish them from Mineral Resources as defined by CRIRSCO and USGS). The preferred parameter to describe the stock available for all of humankind would be the Ultimately Extractable Resources (or Extractable Global Resource), but this is impossible to determine because of our inability to predict what will ultimately be extracted in the future as technology advances and economic and social conditions evolve. Crustal Content is the second best parameter available and CML recommends using it as the baseline with other parameters providing an understanding of the sensitivity of the result to the choice made [8]. Unfortunately, such sensitivity analysis may not assist decision-making, because contradictory indications can often be the result. This is because USGS Reserve Base and Economic Reserve (Mineral Reserve) data involve economic considerations not directly related to resource depletion (such as structure of individual material markets, social conditions reflected in labor costs, negotiating power of mining companies and relative cost of identifying new reserves).

2.2.3. Supply as an Alternative Safeguard Subject

Torsten Hummen (Researcher, Fraunhofer ISI, Karlsruhe, Germany) introduced raw-materials criticality assessment as it is developed and practiced by the European Union. Whereas $\text{ADP}_{[\text{Crustal Content}]}$ looks at environmental impacts on the resource itself (depletion of natural stocks over the long term), criticality assessment looks at short-term impacts on an economy due to disturbances in a supply chain. As for classical risk management [11], criticality typically has two dimensions—a supply risk dimension and an economic importance dimension, which gives an idea of the potential consequences of a supply disruption. Criticality assessment is not yet an internationally standardized method. Criticality is tied to a particular viewpoint, *i.e.*, no raw-material is critical itself in an absolute sense, but it may be critical to somebody somewhere, under the prevailing conditions at some point in time. For example, heavy rare earth elements are considered critical for EU manufacturing in the period 2014–2024 because of their relatively high economic importance for the EU economy and the relatively high risk associated with their supply to the EU. Criticality assessment highlights current issues and informs policy or business decisions. As criticality is a relative assessment, there is no one correct place to draw the line between critical and non-critical raw-materials. In the EU, expert judgment and benchmarking with real-world markets (e.g., that of tantalum) have informed placement of the thresholds. LCA, on the other hand, is an internationally standardized methodology [7]. The environmental impact assessment of established, already employed technologies is the standard application of LCA. There are a number of questions about whether it is appropriate to integrate criticality or supply risk issues (not directly related to environmental impacts) into the Natural Resources AoP of LCA. Though Life Cycle Sustainability Assessment (LCSA) might be a more appropriate place for such assessments, current difficulties related to interdependency of criteria may increase there.

2.3. Paths Forward

Having attempted to bring delegates from different backgrounds to a shared level of basic understanding, the third session of the workshop centered on how better to employ life-cycle thinking in meeting decision-makers' needs related to abiotic raw-materials. The discussions were therefore designed to help ensure that the basis of future research is clear across the relevant disciplines.

2.3.1. Potential Paths Forward and Some Dead-Ends

Pär Weihed (Professor, LTU, Luleå, Sweden) summarized an International Journal of Life Cycle Assessment article he had recently co-authored: "*Mineral resources in life cycle impact assessment—defining the path forward*" [4]. He recommended a multi-stakeholder report titled "Breaking New Ground" [12] to all participants as an invaluable reference for assessment of potential impacts of the use of abiotic raw-materials. Current LCA models introduce unacceptable levels of uncertainty and are not working correctly as decision-making tools. "USGS data are intended to inform about each individual commodity's market conditions and can only be correctly interpreted together with the qualitative information provided in USGS commodity summaries" [4]. Harmonized terminology should be used so that LCA practitioners can build better mutual understanding with the mineral industry. Only Crustal Content data are stable and comprehensive enough to support a physical estimate of ADP—if that is desired and deemed useful. Some more promising tools are being explored within LCSA for assessing the *availability* of abiotic materials, which is defined at any given moment in time by market demand, politics, markets and technology. Observed periods of decline in average ore grades must neither be interpreted as a sign of depletion, nor as an indicator of reduced availability. In a circular economy, metals must be regarded as flows and not stocks and all five forms of capital (*i.e.*, natural, manufactured, human, social and financial capital) that are critical in the context of future abiotic raw-materials availability should eventually be considered within an LCSA tool.

2.3.2. Environmental Depletion and Economic Scarcity

Laura Schneider (Manager Environmental Issues, econsense, Berlin, Germany) presented one of the tools previously mentioned—the economic resource scarcity potential model (ESP, [13]). The ESP model allows for an assessment of raw-material availability beyond geologic finiteness and enables an identification of potential supply risks associated with the use of abiotic raw-materials. ESP defines "scarcity" as limited supply of a demanded raw-material, which could either be caused by depletion of physical stocks (long-term concern) or caused by constraints in the supply chain (short-term concern). Potential physical and economic drivers of scarcity could create direct constraints upon raw-material provision capability and environmental and social drivers could create indirect constraints. Because raw-material provision capability is potentially affected by all these constraints, it should be assessed with a multi-dimensional approach (e.g., LCSA) (here, raw-material provision capability—or supply—is the safeguard subject that can introduce risk to the studied system, whereas LCA is designed to assess the impacts of the studied system upon the external environment). Schneider *et al.* [14] further propose that ADP assessment should be extended to include anthropogenic stocks (potential secondary raw-materials) in its scope. $ADP_{[Crustal\ Content]}$ and ESP provide different information for different decisions. For example, $ADP_{[Crustal\ Content]}$ highlights the use of nickel in hybrid cars, whereas ESP highlights use of rare earths in the same hybrid cars. Comprehensive assessment of abiotic raw-material provision capability, including physical, environmental, economic and social constraints should complement and enhance current LCA practice.

2.3.3. Possibilities in Life Cycle Sustainability Assessment

Guido Sonnemann (Professor, Université de Bordeaux, ISM, TALENCE cedex, France) presented a proposed framework for integrating criticality of raw-materials into LCSA [15]. A new perspective was called for to move from assessing geological stock depletion to including security of supply aspects—as criticality assessment and some water scarcity assessment methods do. LCSA could integrate environmental, social and economic impacts of the studied system. For both water and other raw-materials, a greater geographical explicitness of sophisticated LCA models could take account of variation in climate-related and geopolitical supply risks. Sonnemann *et al.* [15] propose a framework and ISM continues to develop models for individual strands of the framework. The complementarity of criticality assessment and LCA of products suggests there is high potential for LCSA to answer stakeholders' raw-materials concerns. Data generated for LCA can provide information about abiotic raw-material use that can be usable in LCSA, but these data are more valuable the more geographically explicit they become. Supply risk is an economic problem that is perceived differently in various parts of the world and can be addressed in the full LCSA framework—not by isolated indicators hidden in an environmental LCA or footprint result (here, it is proposed that LCSA assess the studied system's contribution to increased supply risk for others, which is consistent with the general life cycle approach of assessing impacts of the studied system upon its surroundings). Using other tools to address the capability gaps left by LCA regarding raw-materials is one way to support better decision making. The Natural Resources AoP needs to be rethought by developing a multi-dimensional approach as part of LCSA—going beyond environmental LCA.

2.4. Discussion

Discussions throughout the day confirmed that there is no common understanding about what the Natural Resources AoP represents and how impacts upon it should be assessed (see also [3,8]). Part of the confusion comes from different and overlapping definitions of key terms in two key areas.

Firstly, whereas most LCIA literature refers to assessing resource *depletion* as an environmental impact, most decision-makers, stakeholders, and researchers try to understand resource *availability* as a sustainability issue that may either impinge upon the studied system or arise from it (here, we have chosen to use the definitions proposed by [4]).

Secondly, while the generators and users of Mineral Resources and Mineral Reserves data use specific definitions of each, LCA-practitioners use the term *reserve* more generally and English-speakers use the term *resource* to refer to a Mineral Resource as well as to a material in its own right.

The CML $ADP_{[Crustal\ Content]}$ method addresses resource *depletion* in terms of reductions of the Earth's geological stocks and the entire Crustal Content is not a Mineral Resource and is therefore not relevant to raw-material *availability*. On the other hand, whereas the International Life Cycle Database (ILCD) Handbook proposes that the CML $ADP_{[Reserve\ Base]}$ method be used, USGS Reserve Base data incorporate economic considerations not directly related to resource *depletion*. The group heard that the ILCD Handbook also redefined the aim of ADP to reflect *availability* of resources for human use, rather than *depletion* potential [16]. This is not trivial—depending on whether *depletion* or *availability* is assessed in an LCIA, one is either dealing with an environmental or an economic issue and workshop participants had seen during the day that contradictory material or product selections can and do result.

Apart from this, there is the problem that it has not been possible to implement the ILCD Handbook recommendation because the USGS had ceased estimating Reserve Base when the Handbook was adopted. This means that calculations of $ADP_{[Reserve\ Base]}$ now rely on obsolete data. After the US Bureau of Mines closed, the USGS discontinued its Reserve Base estimates. Each annual USGS Mineral Commodity Summary includes a discussion of world resources for a given commodity. From 1996 until 2009, Reserve Base estimates were only updated with changes in reserves because available updates on the non-reserve component of the Reserve Base were insufficient to support defensible Reserve Base estimates. Therefore, starting with Mineral Commodity Summaries 2010, publication of a Reserve Base was discontinued [17].

Application of $ADP_{[Reserve\ Base]}$ requires regular updating of characterization factors because Mineral Resources and production change over time. The group discussed how the lack of such updates had serious ramifications for the current Product Environment Footprint (PEF) pilot project of the EU, as it had adopted the ILCD Handbook recommendation in its rules for participants. One of the European Union's intended uses of its PEF Guide and relevant PEF category rules is to support claims about the *environmental* superiority or equivalence of a product when compared to others that perform the same function [18]. If results using $ADP_{[Reserve\ Base]}$ only are used in this way based on obsolete data, it cannot be considered good practice and will certainly lead to misguided claims about environmental performance. To illustrate the dangers of miscommunicating about environmental performance, one participant raised the possibility that a bridge designed to minimize its environmental footprint, could soon afterwards be assessed with a sub-optimal footprint due only to prevailing economics changing $ADP_{[Reserve\ Base]}$ characterization factors—not because of any change in the environmental performance of the bridge. Should the bridge then be replaced?

Given the consensus on the above aspects, different views were expressed as to the usefulness of the $ADP_{[Crustal\ Content]}$ for assessing *availability* of raw-materials. Some academics argued that partial *depletion* of geological stocks could contribute to reduced *availability* of raw-materials over the very long term. That is, a raw-material may become less available to future generations even if functionally it is replaced by other materials or technologies. Geologists remained concerned that if *availability* is to be assessed, Crustal Content is an inappropriate yardstick to use because much of it can safely be assumed to be unavailable. Most participants seemed to agree that *availability* was an economic issue more meaningfully addressed within a comprehensive LCSA framework.

At the request of CML, it was agreed that in future discussions it should always be specified which particular CML option for ADP calculation is being referred to. The ILCD Handbook of the European Commission Joint Research Centre contradicts CML Guidance by specifying use of USGS Reserve Base data instead of Crustal Content data. When this particular ILCD Handbook recommendation is criticized, it should be clearly stated rather than criticizing the whole ADP method as published by CML.

Some extra suggestions were made to advance the search for a suitable tool to assess *availability* of raw-materials. The available quantity of raw-materials at any given time is always a subset of the total natural occurrence of that material. Therefore, there was some agreement across disciplines that available quantities of raw-materials (e.g., any class of Mineral Resources or Mineral Reserves) should be modeled as fund resources (rather than stock resources) and that dissipative outflows from studied systems—rather than inflows to them—were the concern to address in order to maximize continued *availability* of raw-materials. This would also give recognition to the fact that raw-materials are not always consumed or dissipated, but often remain available as an anthropogenic source for recycling. It may prove more practical and relevant to use data on dissipative outflows as a proxy for reduced *availability* (See also [3]).

Finally, although several participants were working on stand-alone frameworks to include assessment of raw-material *availability* and supply risks, it was acknowledged that a tool-box approach may prove to be more appropriate and that eventually only one set of globally agreed tools should be promoted as good practice in the field.

3. Conclusions

Over the last 20 years, the idea that Natural Resources exist separately from Human Health and the Natural Environment has been maintained in LCA theory and yet, as this workshop showed, the idea is not a simple one. Dictionary definitions of the term *resource* invariably refer to *availability* to or *use* by humans. Some contend that Natural Resources are components of the Natural Environment seen through a utilitarian lens. It is easier to understand that *health* and *environment* obey their own fundamental laws (*i.e.*, the laws of thermodynamics and quantum mechanics) and exist in some form without human interaction. Such a distinct set of environmental mechanisms is missing for Natural Resources, which makes them difficult to characterize or evaluate within the logical construct of LCIA.

To better understand each other, delegates at this Workshop often found it necessary to talk instead of *raw-materials*. As defined by leading geological institutions, Mineral Resources and Mineral

Reserves are snapshots of raw-material *availability* at a given point in time given prevailing market conditions. They do not represent the total stock of material available to humankind for all time and they are not necessarily diminished by the mining of ore. It is impossible to predict future human capabilities and therefore how much of a raw-material will ultimately prove extractable from the Earth.

CML therefore considers that Crustal Content is the best available baseline to determine resource *depletion* and recommends using it as such in LCIA. European Commission Joint Research Centre Guidance addresses materials in terms of *availability* for human use and suggests $ADP_{[Reserve\ Base]}$ should be used to express that. However, USGS Reserve Base data are obsolete (no alternative source of Reserve Base data exists) and largely underestimate long-term raw-material *availability* for human use. If used to support claims about the environmental performance of a product or organization, $ADP_{[Reserve\ Base]}$ will certainly lead to misguided claims being made.

The weight of available evidence suggests that extraction of natural resources from the environment is not decreasing foreseeable *availability* of natural materials for human use. Even observed periods of decline in average ore grades have been accompanied by significant increases in Mineral Reserves (See also [4,19,20]). Such ore grade trends can neither be interpreted as a sign of depletion, nor as indicating reduced *availability*. Raw-material *availability* and the associated supply risks are overwhelmingly the result of economic, technological and geo-political forces and most participants seemed to agree that such an AoP will be more meaningfully addressed within a comprehensive LCSA framework rather than limited to an environmental LCA or Footprint.

To better define how life cycle thinking can help answer questions related to the extraction and use of abiotic raw-materials, it would be helpful to clearly distinguish *availability* from *depletion* and clarify which of these is estimated by each of the existing LCIA methods, so that results can be correctly reported in the most appropriate framework. It could also be a helpful convention to refer to Natural Resources used in studied systems as *raw-materials* and to clearly distinguish them from Mineral Resources and Mineral Reserves as defined by CRIRSCO and USGS.

Without a shared vision, agreed terminology and common incentives, collaboration across disciplines on assessment of impacts of abiotic raw-material inputs to production and consumption systems will continue to be very difficult. The only satisfactory path forward is more dialogue between experts in the fields of LCA, commodities trading, environmental science, exploration geology, industrial ecology, technological innovation, metallurgy, mineral economics, minerals policy, product policy and sustainable development.

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